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An Assessment of Unglazed Solar Domestic Water Heaters

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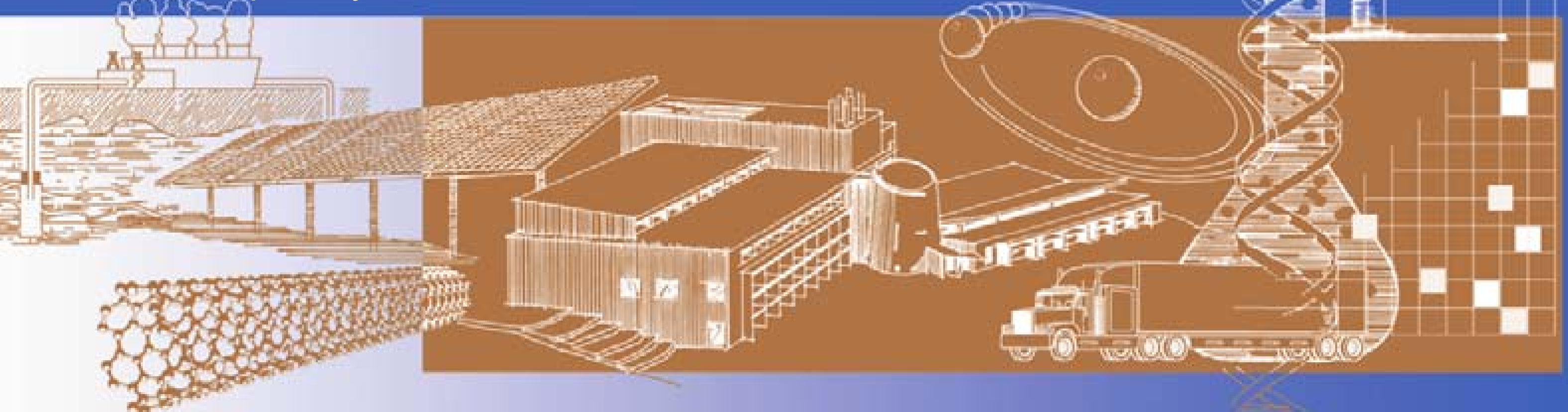

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AN ASSESSMENT OF UNGLAZED SOLAR DOMESTIC WATER HEATERS

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ABSTRACT

This paper investigates cost-performance tradeoffs in replacing glazed collectors with unglazed ones in solar domestic water heaters (SDWH). The collector models are based upon accepted test standards, with the unglazed model explicitly including wind and sky infrared flux. A conventional glycol system is modeled, with glazed and unglazed collectors. Annual efficiency for a 40-ft^2, unglazed SDWH is approximately constant across the United States at 21±1%. This efficiency is slightly more than 1/2 that of an equal-sized glazed system with selective absorber coating, and ~2/3 that of a glazed system with nonselective coating. Considering an SDWH system, exchanging glazed collectors for unglazed ones of the same size generally increases the cost of saved energy (C_{sav}, defined as total-cost/total-savings). However, if the unglazed collector area A_{ungl} is increased to compensate for reduced performance, C_{sav} may significantly decrease, as long as $A_{ungl}/A_{glaz} < \sim 5$. General expressions for $C_{sav,ungl}/C_{sav,glaz}$ are derived for cases of equal collector area and equal savings (where the unglazed area is increased until savings are equal). If larger areas are not problematic, unglazed SDWH can offer lower C_{sav} at lower first cost.

1. INTRODUCTION

Unglazed polymeric collectors have long been used in solar pool heating systems, and they dominate the U.S. solar market [$A_{ungl,sold} \approx 20 * A_{glaz,sold}$ (1)]. With low cost and good performance, solar pool heaters can attain simple payback < ~5 years, corresponding to ≥ ~20% return on investment. In the United States, such favorable economics are likely needed to create significant markets for SDWH, as in (2,3). External factors such as subsidies and/or fossil fuel cost escalations may dominate future SDWH market growth (as happened in the early 1980s), but the focus here is on potential hardware cost reduction, as in (3). Since unglazed collectors can be significantly lower in cost than glazed collectors, there is some cost reduction potential for unglazed SDWH, and assessment of that potential motivated this work.

At 40 ft^2 size in large quantities, the ratio of the unit area cost of an unglazed polymer pool collector to that of a glazed collector ($R_{\$ungl/\$glaz}$) is ~20% (3), a very significant cost reduction. However, impact on system cost depends also on the other costs, shown in Fig. 1. When the other costs are low, as in the do-it-yourself case in Fig. 1, unglazed SDWH *systems* cost significantly less than glazed (40% in the Fig. 1 example), and could be attractive. For the new-construction glazed case (our focus here), the other costs are more significant. System cost reduction is fractionally less (16% in the example).

Other groups have been working on unglazed SDWH, and they are being marketed by firms in India (4) and Europe (5). Prototypes of unglazed SDWH using conventional roofs as absorbers have been tested (6). Larger-scale, roof-integrated unglazed systems reducing space conditioning and DHW loads are considered in (7,8). However, performance and costs for unglazed SDWH are generally not grasped as well as for glazed SDWH. A cost-performance comparison between glazed and unglazed SDWH with consistent energy modeling is the objective of this paper. We describe the modeling, simulate energy savings, and give general solutions for C_{sav} in two cases, where the collector areas are equal (=A case) and where the system savings are equal (=Q case).

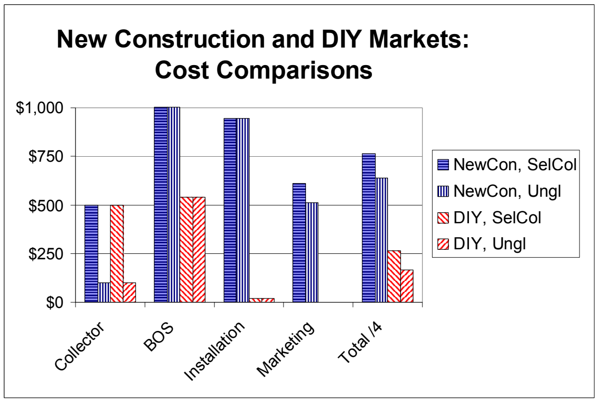

Fig. 1: First cost components of a glycol system in new construction (NewCon) and do-it-yourself (DIY) markets, with glazed and unglazed collectors.

2. PERFORMANCE MODELING

Performance of unglazed collectors is reasonably well-understood. Fig. 2 shows efficiency (η) of the glazed and unglazed collectors used here vs. the "operating parameter" ($\gamma \equiv \Delta T_{in\text{-}amb}/I_{sun}$). The unglazed collector has a higher loss coefficient (steeper slope). The performance of unglazed collectors in pool heating applications is good because γ values are mostly small in that application (e.g., 0.01 $^oC\text{-}m^2/W$ @ $\Delta T_{inlet\text{-}ambient} = 5^oC$, I_{sun} = 500 W/m^2). Thinking has been that, since the operating parameter is much larger for SDWH (e.g., 0.04 $^oC\text{-}m^2/W$ when $\Delta T_{inlet\text{-}ambient}$ = 20°C, I_{sun} = 500 W/m^2), an unglazed collector would operate too inefficiently.

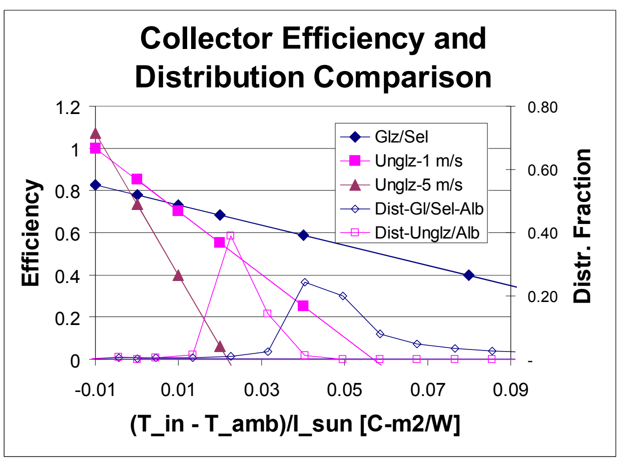

Fig. 2. Collector efficiencies vs. the operating parameter γ, glazed and unglazed (at two v_{wind}), in Phoenix, AZ. Also shown are the distribution functions γ_{glaz} and γ_{ungl}.

Annual distributions of the operating parameter γ are also shown in Fig. 2. For the glazed system, the γ distribution peaks at about twice that of the glazed, indicating the glazed system operates hotter. Although $\eta_{ungl} \approx 0$ where the γ_{glaz} distribution is largest, the efficiency of the unglazed system at lower v_{wind} is reasonably good where γ_{ungl} is large, and the unglazed SDWH can still save substantial energy.

An empirical characterization of the collectors always provides the highest confidence. The unglazed collector model is based on an international test standard that explicitly incorporates wind and sky infrared (9,10). The unglazed collector efficiency is expressed as

$$\eta_{col} = F_r\alpha_n K(\theta) - F_r U_l(T_{in} - T_{amb})/I_{net}. \qquad (1)$$

I_{net} includes both short-wave solar and net sky blackbody radiation between sky and ambient temperatures, $I_{net} = I_{sun} - \varepsilon/\alpha * I_{IR}$. Efficiency is relative to I_{net}. F_rU_l and $F_r\alpha_n$ are taken as linear in v_{wind} (10), $F_r\alpha_n = a_o - a_1 v_{local}$, and $F_rU_l = b_o + b_1 v_{local}$. a_i, b_i values used here are given in Table 1. The largest uncertainty comes from estimating terrain and shielding affects on v_{local}. It is assumed here that v_{local}/v_{TMY} = 0.3, as in (2). Uncertainty in this ratio (~0.2 - ~0.5), causes ~10%-20% variation in performance and dominates uncertainty in the analyses here.

The glycol system simulated here is shown in Fig. 3. Key system parameters are given in Table 2, with more details in (11). Simulations of performance were done with TRNSYS (12). Daily draw volume is kept fixed at an invariant 64 gal (242 l), which is the standard "rating load" in the U.S. (13). The time-of-use profile assumed is a typical "double-humped" profile, taken from (14). Mains inlet temperature scales directly with site annual average temperature, and varies sinusoidally with time of year, as in (14). Storage/area is set at 1.5 gal/ft^2.

3. PERFORMANCE RESULTS

U.S. maps of the annual savings for a 40 ft^2 glycol SDWH with a selective glazed collector and an unglazed collector are shown in Figs. 4 and 5, respectively. These maps tend to directly mimic maps of the annual incidence of solar radiation, because the system annual efficiency (see below) is relatively constant, independent of location. Efficiency decreases relatively for systems that are "oversized" and saturate significantly during the summer (system "overheats" and losses increase, implying lowered efficiency). This effect shows up in the drop in savings in southern Florida, where the loads are lowest because mains inlet temperature is highest. A similar drop-off in efficiency that occurs for some southwestern locations is not evident in the performance maps.

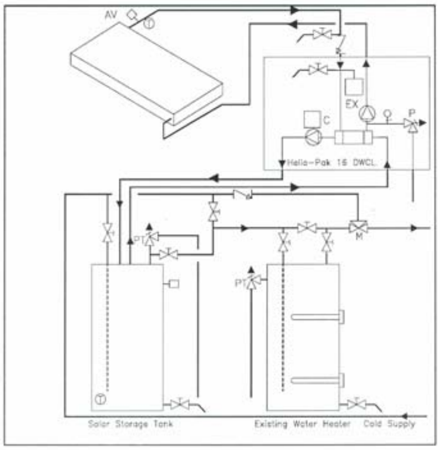

Fig. 3: The Heliodyne indirect glycol system, Heliopak model. Taken from (13), where symbols are defined.

TABLE 1: COLLECTOR PARAMETERS

Collector	$F_r\,\tau\alpha_n$	F_rU_l [W/m^2]
Selective glazed[1]	0.779	4.77
Nonselec. glazed[1]	0.768	7.245
Unglazed[2]	$0.88 - 0.029 * v_{local}$	$10.24 + 4.69 * v_{local}$

1. From the SRCC OG100 directory, posted at (13).
2. From (10), test results for a pool collector.

TABLE 2: BASE-CASE SYSTEM PARAMETERS

Collector (metal-glass selective)	
Area	3.72 m^2 (40 ft^2)
Slope	33.7°
Solar Tank (pressurized)	
Volume	0.227 m^3 (60 gal)
U-value	0.556 W/m^2-°C
Auxiliary Tank (pressurized)	
Volume	0.15 m^3 (40 gal)
U-value	0.981 W/m^2-°C
Setpoint Temp.	51.7 °C (125 °F)
Envir. Temp.	20 °C (68 °F)
Piping (hard copper)	
Length (sup. + ret.)	15.24 m (50 ft)
U-value	2.27 W/m^2-°C

SDWH performance can be usefully described by an annual efficiency $\eta_{ann} \equiv Q_{sav,ann}/Q_{inc,ann}$. Fig. 6 shows η_{ann} vs. the site annual average temperature for a 40 ft^2 SDWH with three different collectors: selective-glazed, non-selective-glazed, and unglazed collectors. In each case, the efficiency is reasonably constant across the United States. That η_{ann} across sites is constant when system size and load volume are kept constant is noted in (15) for a glazed glycol system. Here, $\eta_{ann,glaz}$ is ~39% ± 1%, and $\eta_{ann,ungl}$ is ~21 ± 1%, so that $R_\eta = \eta_{ann,ungl}/\eta_{ann,glaz}$ ~0.54; i.e., *the unglazed system saves slight more than 1/2 as much as the glazed selective system, at 40 ft^2* size. R_η is ~0.64 for a nonselective glazed SDWH (12). Nearly identical efficiencies with the same three collectors were reported in (12) for a typical drainback system. A thermosiphon system showed slightly lower efficiency with non-selective and polymer collectors (12).

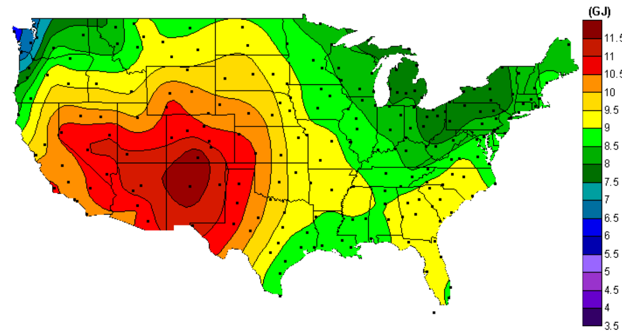

Fig. 4: U.S. map of annual savings (GJ) for a 40 ft^2 glycol SDWH with a glazed, selectively coated collector.

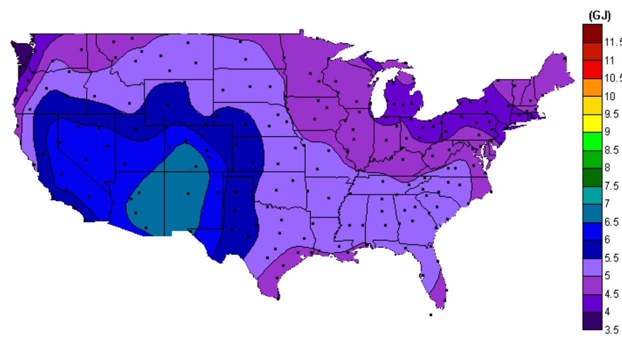

Fig. 5: U.S. map of annual savings (GJ) for a 40 ft^2 glycol SDWH with an unglazed collector (same scale as Fig. 4.)

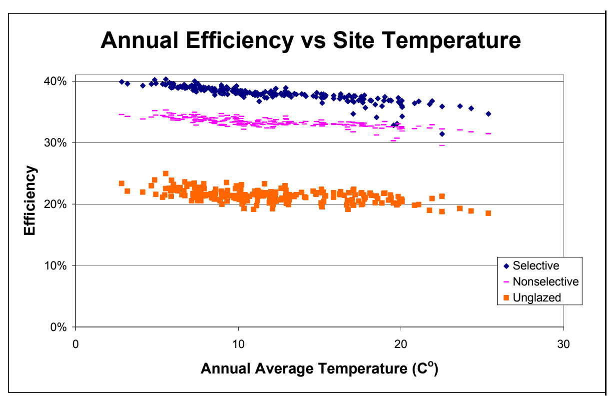

Fig. 6: η_{ann} vs. $T_{amb,avg}$ for a 40 ft^2 SDWH, with two glazed collectors and an unglazed collector.

A continental U.S. map of the efficiency ratio R_η for 40 ft^2 systems is given in Fig. 7. R_η is fairly constant at 0.54 ± 0.02. R_η is lower along the coasts and in the Midwest, where winds tend to be higher. R_η also tends to be lower where the load is lower, as in southern Florida and Texas. R_η is higher in spots with lower wind velocities and higher loads. Because of the low spatial density of TMY sites, the contours in Fig. 7 are somewhat dependent on the contouring algorithm and should not be taken too literally. Although glazed collector performance is also affected (slightly) by the wind, this variation is not taken into account. Note that the maximum deviation of R_η (± 0.05) is less than 10% of the average ratio, and it is a useful approximation that $Q_{sav,ungl} \approx K^* Q_{sav,glaz}$. K is a function of system size and collector types (e.g., 0.54 with the selective glazed collector at 40 ft^2 size).

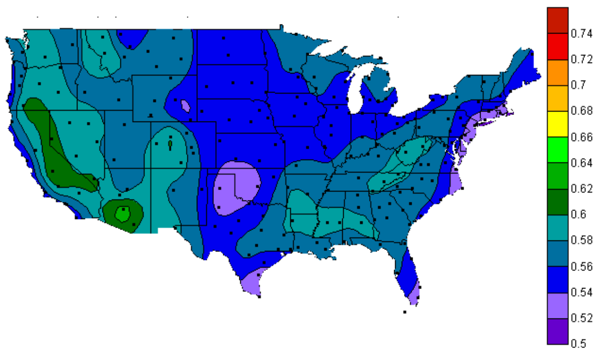

Fig. 7. U.S. map of the ratio $\eta_{ann,ungl}/\eta_{ann,glaz}$ for a 40 ft^2 glycol system. The glazed collector is selective.

Fig. 8 shows the solar fraction of the glazed and unglazed SDWH vs. A_{col}, at three sites. The glazed system saves more than the unglazed system at all areas. Starting with the smallest area, the glazed system's performance increases with area (which increases system temperature) faster than that of the unglazed system. The glazed systems in Miami and Albuquerque saturate at ~7 m^2. The glazed system did not saturate in Madison, with higher loads and lower radiation. None of the unglazed systems showed saturation (up to maximum $A_{col} = 20\ m^2$). At a given area, savings are smaller in Madison because the incident solar radiation is less. The Miami glazed system slightly outperforms the Albuquerque glazed system, even though radiation is lower, because the Albuquerque system saturates more in summer; this ordering reverses for unglazed SDWH, which don't saturate in the summer.

4. COST-PERFORMANCE TRADEOFF

Because the unglazed collector changes both first cost and savings, it is useful to compare a single normalized metric between systems (2,3,16): $C_{sav} \equiv \$_{sys,total}/Q_{sav,total}$. The total system cost $\$_{sys,total}$ includes the present value of repair costs (2,16). C_{sav} normalizes for the simultaneous effects of lowered system cost and lowered performance. It also compares directly with the cost of energy from conventional fuels. It is a commonly-used metric in tradeoff analysis, as in (2,3).

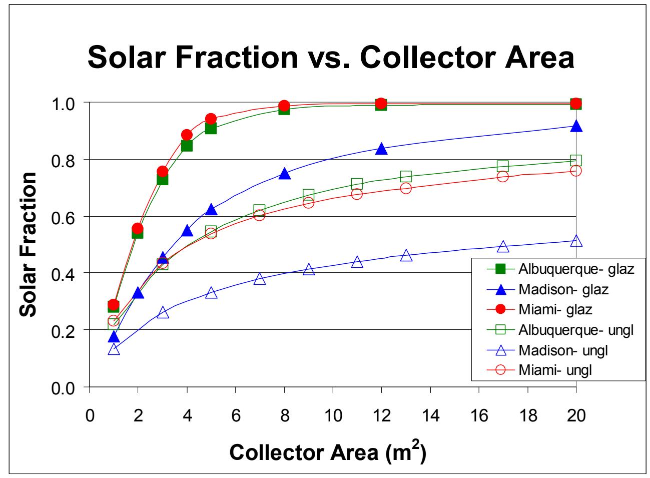

Fig. 8: Solar fraction vs. collector area for a glazed and unglazed collector at three sites: Albuquerque, NM, Madison, WI, and Miami, FL.

There are two useful cases considered here: equal A_{col} (=A) and equal Q_{sav} (=Q). In the =A case, the unglazed collector has the same area as the glazed collector. Collector cost is reduced by 80%, but the system cost reduction depends on the ratio $R_{\$col/\$sys}$ and savings are also reduced [$Q_{sav,ungl}/Q_{sav,glaz}$ ($\equiv R_{Q,=A}$) < 1]. $R_{Q,=A}$ is a function of the collector area A_{col}, as shown in Fig. 9. The ratio initially decreases as A_{col} increases, because system temperatures are increasing and the unglazed system operates less efficiently. When the glazed system starts to saturate, the unglazed system is still increasing in savings. Thus, $R_{Q,=A}$ starts to increase with area (not true for Madison because saturation did not occur in Madison). Assuming that only the collector cost differs between the glazed and unglazed SDWH, it is easy to show that for equal collector areas, the ratio $R_{Csav,=A}$ can be expressed as

$$R_{Csav,=A} = [1 - R_{\$col/\$sys}(1 - R_{\$ungl/\$glaz})]/R_{Q,=A}. \qquad (2)$$

$R_{Csav,=A}$ depends on the ratios $R_{\$col/\$sys}$, $R_{\$ungl/\$glaz}$, and $R_{Q,=A}$. Contours of $R_{Csav,=A}$ in the plane ($R_{Q,=A}$, $R_{\$col/\$sys}$) are shown in Fig. 10. Unglazed systems are more cost-effective than glazed systems when $R_{Csav} < 1$, as in the upper right corner of Fig. 10. This region corresponds, e.g., to pool systems. Unglazed systems are less cost-effective when $R_{Csav} > 1$, as in the lower left side of Fig. 10. This region corresponds to cases where BOS and installation costs are significant (i.e., low $R_{\$col/\$sys}$), as in typical new construction or retrofit cases.

For the =Q case, the unglazed collector area is increased such that $Q_{sav,ungl} = Q_{sav,glaz}$, with $A_{ungl}/A_{glaz} \equiv R_{A,=Q}$. Fig.

11 shows $R_{A,=Q}$ as a function of $A_{col,glaz}$. At small sizes, $R_{A,=Q}$ is relatively small, because operation is at lower temperatures where the unglazed system is relatively efficient. As area increases, $R_{A,=Q}$ increases because increased system temperatures further favor the glazed collector. It is not understood why $R_{A,=Q}$ is significantly higher for Miami beyond ~$2m^2$. For Albuquerque or Madison, an unglazed system of ~12 m^2 provides energy savings equivalent to a ~3 m^2 glazed system, with ~50% larger area needed for =Q in Miami. It is easy to show that for the =Q case, the ratio $C_{sav,ungl}/C_{sav,glaz}$ ($\equiv R_{Csav,=Q}$) is

$$R_{Csav,=Q} = [1 - R_{\$col/\$sys}(1 - R_{\$ungl/\$glaz} * R_{A,=Q})] \qquad (3)$$

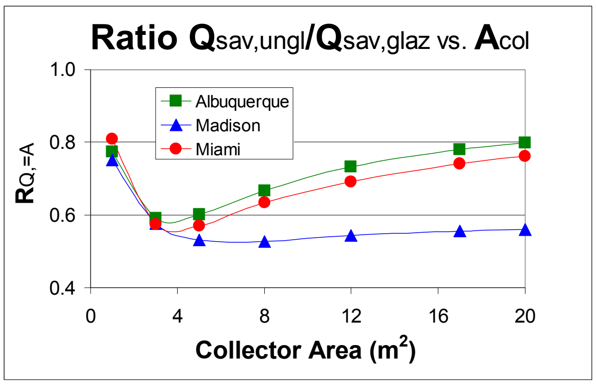

Fig. 9: Plot of the ratio $Q_{sav,ungl}/Q_{sav,glaz}$ ($R_{Q,=A}$) vs. the glazed collector area, for three sites.

Contours of $R_{Csav,=Q}$ in the plane ($R_{A,=Q}$, $R_{\$col/\$sys}$) are shown in Fig. 12. $R_{Csav,=Q}$ is 1 when $R_{A,=Q} = 5$, because we have assumed $R_{\$ungl/\$glaz} = (1/5)$. This break-even point corresponds to A_{glaz} ~2.8 m^2 in Miami, and ~3.3 m^2 at the other two sites. For $R_{A,=Q} <5$, $R_{Csav,=Q} < 1$ and the unglazed is more cost-effective. Note that with $R_{\$col/\$sys}$ ~0.2, and $R_{A,=Q} \sim 4$, the advantage is fairly small, ~5%. Thus, for the =Q case, the larger-sized unglazed SDWH appear cost-effective compared with the smaller-sized glazed SDWH, less so as $R_{\$col/\$s}$ decreases and solar fraction increases. For the general case, it would be expected that for area ratios somewhat near $R_{A,=Q}$, the C_{sav} ratio would be less than one (exact results can be estimated for such cases using Fig. 8 data). The key ratios $R_{A,=Q}$ and $R_{Q,=A}$ were derived for only three sites. Further work is needed to know those ratios for *any* site, although the three sites characterized here give some guidance.

5. CONCLUSIONS

Unglazed SDWH are less expensive than glazed SDWH, but operate less efficiently and yield lower maximum temperatures. System efficiencies were computed to be ~38%, ~33%, and ~21% for a 40 ft^2 glycol system with a glazed selective, glazed nonselective, and unglazed collector, respectively. At equal areas, $C_{sav,ungl} > C_{sav,glaz}$, and that tradeoff is not cost-effective for cases of interest here. However, when the unglazed SDWH area is increased so that $Q_{sav,ungl} = Q_{sav,glaz}$ (possible at lower solar fractions), then the substitution is cost-effective as long as $R_{\$ungl/\$glaz} * R_{A,=Q} < 1$.

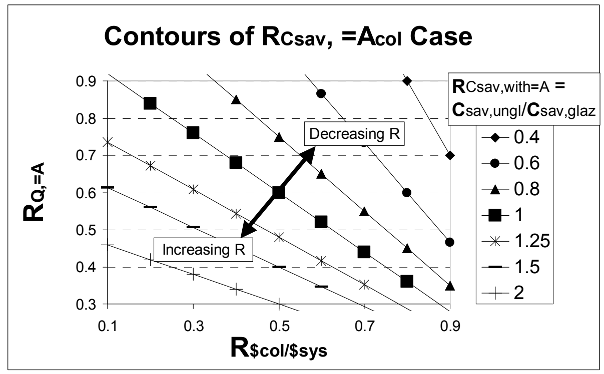

Fig. 10. Contours of R_{Csav} vs. ($R_{Q,=A}$, $R_{\$col/\$sys}$). The collector cost ratio $R_{\$ungl/\$glaz}$ is kept fixed at 0.2.

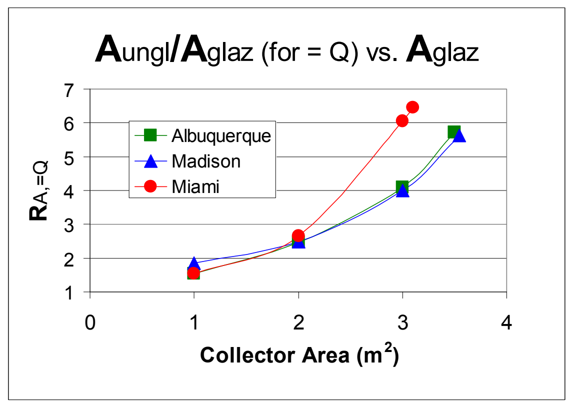

Fig. 11. Ratio of collector areas for =Q ($R_{A,=Q}$) vs. A_{glaz}, for 3 sites. The lines end when the implied $A_{ungl} > 20$ m^2.

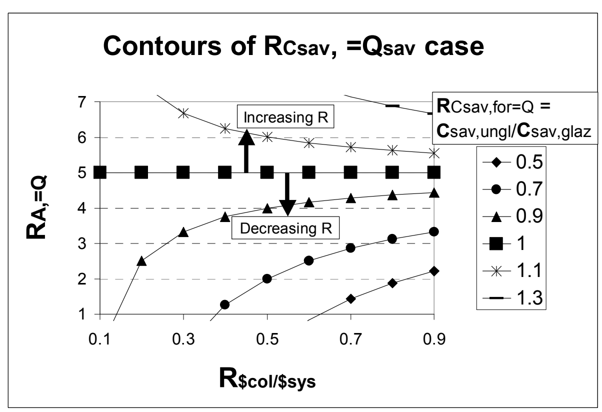

Fig. 12. Contours of $R_{Csav,=Q}$ vs. ($R_{\$col/\$sys}$, $R_{A,=Q}$). The collector cost ratio $R_{\$ungl/\$glaz}$ is kept fixed at 0.2.

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7. NOMENCLATURE

Symbols:

a,b	= Constant coefficients
A	= collector area
C_{sav}	= Cost of saved energy = $\$_{sys}/Q_{sav}$
f_{sol}	= solar fraction
F_r	= Heat removal factor
I	= Solar or infrared incidence (solar power/area)
K	= Incidence angle modifier (IAM) or constant
Q_{sav}	= Energy saved over analysis period
$R_{A,=Q}$	= Ratio of A_{ungl}/A_{glaz} such that $Q_{sav,ungl} = Q_{sav,ungl}$
R_{Csav}	= Ratio of C_{sav}/C_{sav}
$R_{Q,=A}$	= Ratio of $Q_{sav,ungl}/Q_{sav,glaz}$ with equal areas
$R_{\$coll/\$sys}$	= Ratio of glazed collector to glazed system cost
$R_{\$ungl/\$glaz}$	= Ratio of unit area cost, \$ungl/\$glaz
T	= Temperature
U_l	= Collector loss coefficient
v	= Wind velocity (subscripted local or TMY)
\$	= Cost, item as denoted by subscripts
α_n	= Collector absorptivity at normal incidence
ε	= Collector emissivity
η	= Efficiency (collector or system)
θ	= Incidence angle, in IAM function $K(\theta)$

Subscripts

amb	= ambient condition
col	= collector
glaz	= glazed
in	= mains inlet, or inlet to collector
inc	= incident solar on collector
IR	= net infrared radiation between sky and ambient
local	= wind at the collector location
net	= net of short and (ε/α)*(long-wave radiation)
sun	= short-wave radiation
sys	= system
TMY	= Typical Meteorological Year data
total	= total cost or total savings
ungl	= unglazed
η	= efficiency

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